

DEC 2 1 1994

GOLDEN, COLORADO 80401-3393

Proceedings of the Conference and Workshop on Wind Energy Characteristics and Wind Energy Siting 1979

**June 19-21, 1979
Portland, Oregon**

**Sponsored by
the U.S. Department of Energy
and
the American Meteorological Society**

**Coordinated by
Pacific Northwest Laboratory
under Contract EY-76-C-06-1830
Operated for the U.S. Department of Energy
by Battelle Memorial Institute**

PNL-3214

METEOROLOGICAL AND TOPOGRAPHICAL INDICATORS
OF WIND ENERGY FOR REGIONAL ASSESSMENTS*

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INTRODUCTION

Existing wind data provide the primary basis for assessing a region's wind energy potential. However, the existing wind data must be evaluated carefully to determine their representativeness of the site and local area, because wind energy is very sensitive to variations in terrain, vegetation roughness, height above ground, and instrument exposure. Even over flat smooth terrain, large interstation variabilities in the wind power estimates may exist. Simple interpolation between existing data points may not result in a very reliable or realistic analysis, especially in complex terrain and data-sparse areas. This is due primarily to the sparsity of wind data compared to scale of the variation in the wind energy patterns and the topographical influences on the wind. In analyzing the wind energy in complex terrain and data-sparse areas, we must also rely on the use of various indirect indicators of wind energy and an understanding of the physical processes and features that result in high winds in some areas but not in other areas.

* This paper is based on work performed under U.S. Department of Energy Contract No. EY-76-C-06-1830.

Techniques using various indicators of wind energy have been investigated for their application in regional wind energy assessments. The indicators include the use of meteorological and topographical features, botanical features, eolian landforms, public surveys, and model estimates. Botanical indicators, such as flagged trees, have been investigated by Oregon State University (Hewson et al. 1978). Results indicate that vegetation in windy locations displays certain characteristics that allow an estimate of mean wind speeds. Techniques for identifying and using eolian landforms, such as sand dunes, blowouts, and playa lakes, as indicators of wind energy have been described by the University of Wyoming (Kolm and Marrs 1978).

In the Northwest regional wind energy assessment (see page 213), Pacific Northwest Laboratory (PNL) investigated combinations of meteorological and topographical features that are characteristic of high or low wind energy and applied these indicators, as a supplement to existing wind data, in analyzing the geographical distribution of the region's wind energy. This paper describes the various meteorological and topographical features indicative of high or low wind energy, areas where they occur in the Northwest, and methods used in applying the indicators in the Northwest regional wind energy assessment. These indicators are especially useful in complex terrain areas and are applicable to other regions of the United States.

APPROACH

The identification of meteorological and topographical indicators of wind energy followed the evaluation of existing wind data. An important element in understanding the wind characteristics at a site is the location of the site with respect to surrounding terrain features. For this purpose, shaded topographic relief maps and contour maps of the scale 1:500,000 were used to evaluate the locations of wind stations. For example, the elevation of the station as compared to the elevation of surrounding terrain and the proximity and orientation of surrounding terrain features were noted. The anemometer height and exposure (if available) and local site environment (e.g., airport, urban, forest, desert sagebrush, etc.) were considered in evaluating the representativeness of a site's wind power estimates. Even over relatively flat, smooth terrain, airport sites may have as much as a factor of two or more wind power than urban sites only a few kilometers away. For example, the 10-m-level adjusted wind power for Havre, Montana, city and airport locations are 57 and 161 watts/m², respectively. Airport sites, in general, are more representative of exposed locations, since the prevailing power-producing winds are usually parallel to the runway(s).

Sites with high seasonal and annual wind power, particularly in data-sparse or complex terrain areas, were noted for further study of the wind characteristics and terrain features. The influence of topography and meteorological conditions associated with strong wind speeds (e.g., strong surface pressure and thermal gradients, valleys parallel to the direction of prevailing strong winds aloft, etc.) were investigated for sites with existing wind data. Synoptic weather maps were examined to identify characteristic surface pressure and thermal patterns and upper air flow patterns associated with the occurrence of high

winds in certain areas. In particular, weather patterns were noted where some stations showed persistently strong winds while nearby stations (50 to 200 km away) showed light winds. For example, persistent strong winds during summer in the Columbia Gorge and Ellensburg valley corridors of Washington are associated with the occurrence of strong pressure gradients along the Cascade Mountains (see Figure 1). These strong pressure gradients result from cool marine air west of the mountains and warm dry air east of the mountains, since the mountains act as a barrier separating the two different air masses. The relatively dense marine air flows rapidly eastward, from high to low pressure, through low outlets in the mountains, forming corridors of high wind speed extending eastward. The flow is usually quite strong and varies with the diurnal variations of the pressure gradients.

A frequently-occurring winter pattern over the Northwest is shown in Figure 2. Under this synoptic condition, strong pressure gradients exist in the vicinity of the Cascade Mountains and Rocky Mountains. Strong winds can be expected where terrain features enhance the pressure gradient flow. Figures 3 and 4 are schematic illustrations of frequent winter conditions usually associated with strong corridor winds in areas of the Northwest. Cold dense air builds up to one side of the mountain range and spills out through corridors. Under these conditions, the wind speeds on mountain summits may be light, whereas the wind speeds in the mountain corridors are usually strong. Livingston and Whitehall, Montana, are examples of two places in the Rocky Mountains where these strong corridor winds frequently occur. Because these stations are located at the outlets of long valleys extending down from the mountains, they also experience moderate winds associated with the mountain-valley breeze circulation during the warmer months.

This investigation of the weather patterns and topographical influences associated with high or low wind energy areas allowed a better understanding of the geographical distribution of wind energy. The use of these meteorological and topographical indicators was applied to estimate the geographical distribution of power in areas with existing wind data and to infer, by analogy, the wind power in data-sparse areas where similar features exist.

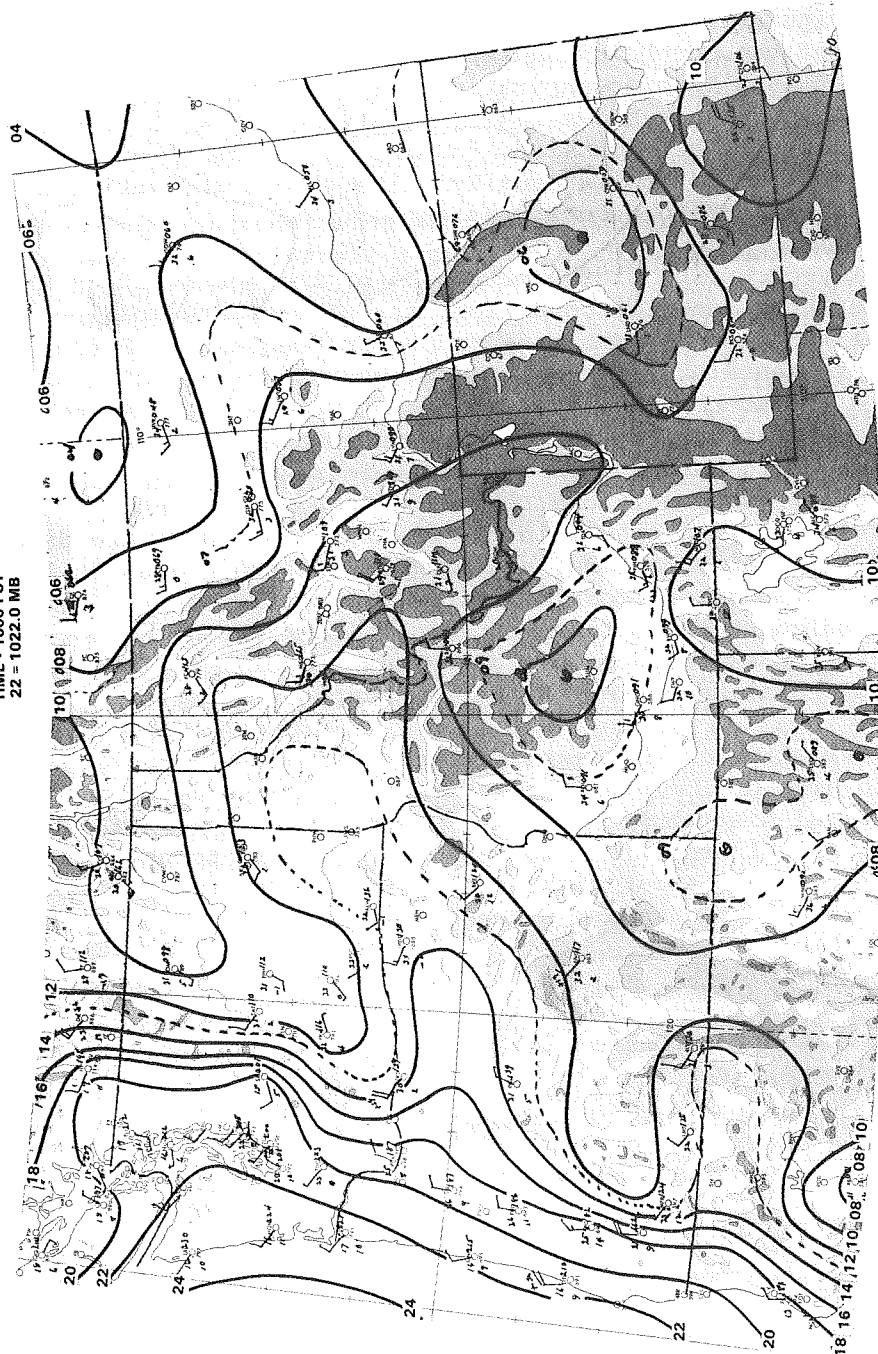
RESULTS

In the Northwest regional analysis, the following combinations of meteorological and topographical features indicative of high wind energy areas were identified:

- A) corridors in areas of frequent strong pressure gradients,
- B) long valleys parallel to prevailing wind direction and extending down from mountain ranges,
- C) high elevation plains and plateaus in areas of strong geostrophic winds,
- D) plains and valleys with persistent strong downslope winds associated with strong pressure gradients,

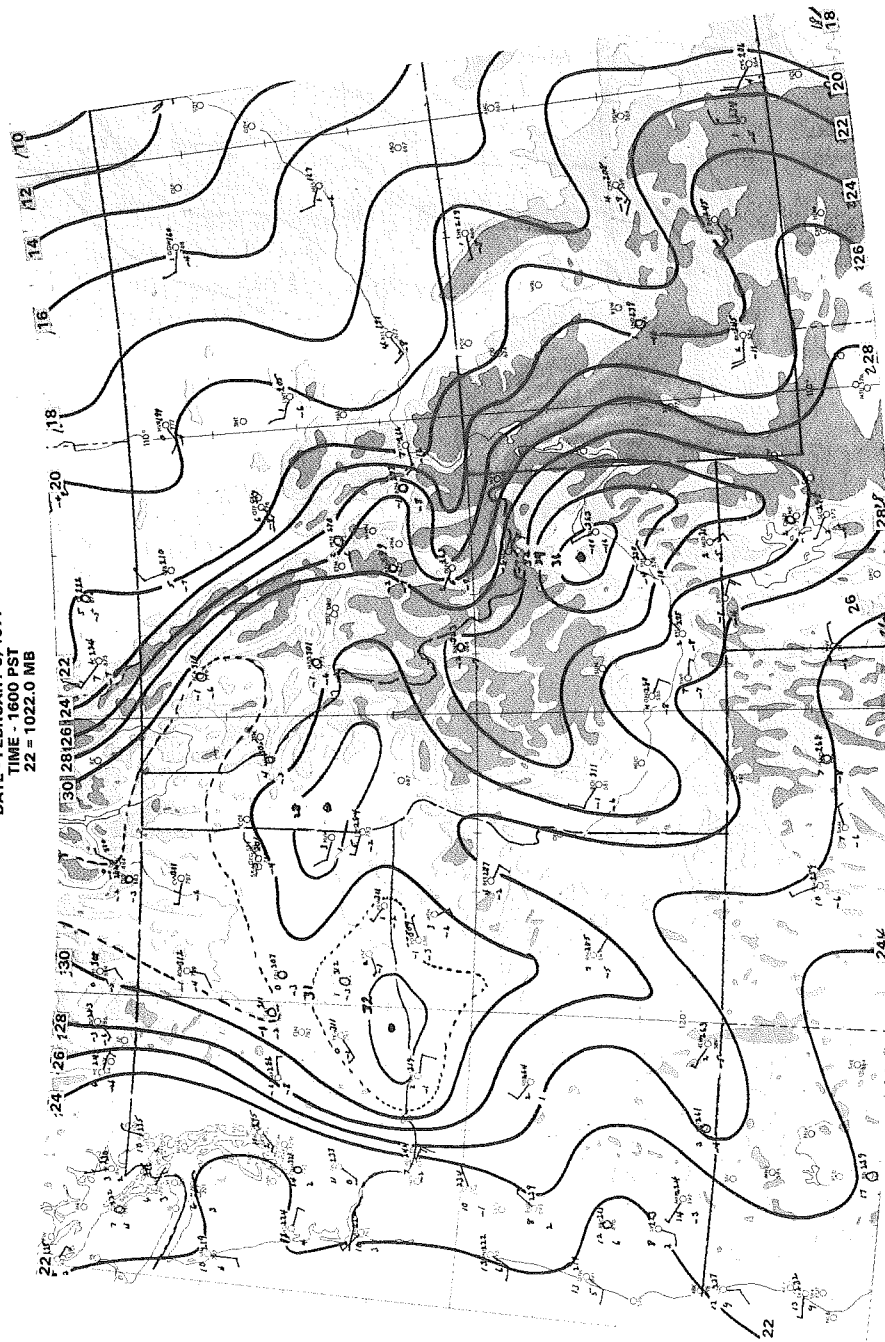
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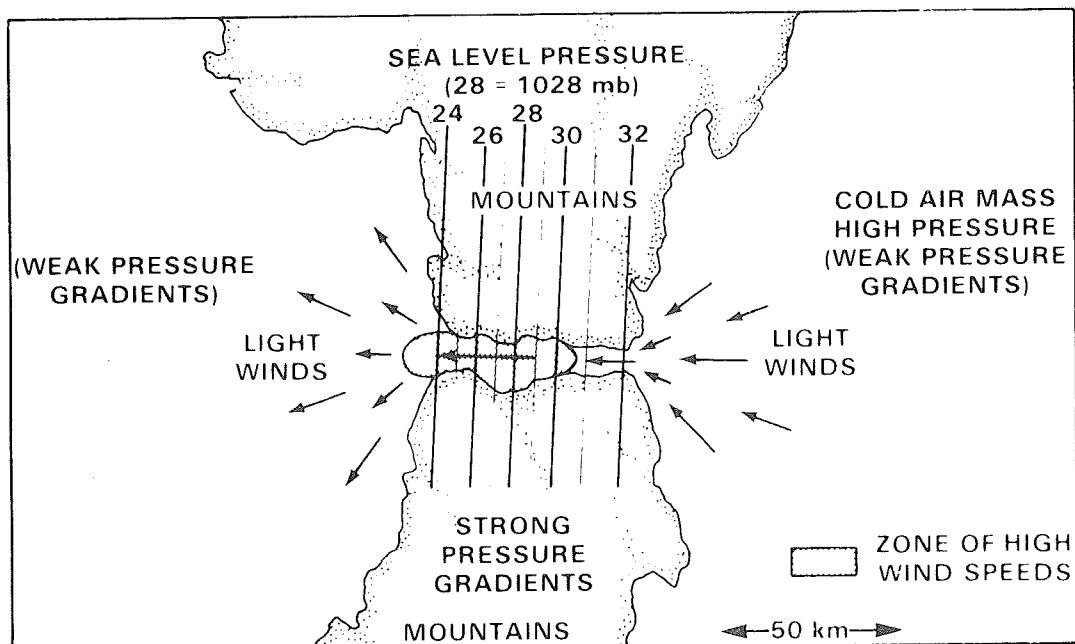


FIGURE 3. Frequent Wind Condition in the Northwest Resulting in Strong Corridor Winds

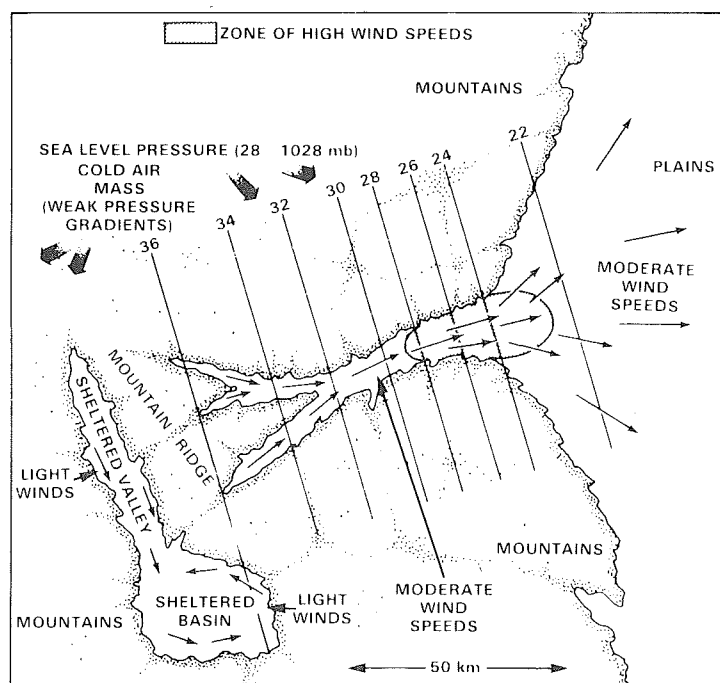


FIGURE 4. Frequent Winter Condition in the Northern Rocky Mountains Resulting in Strong Corridor Winds

- E) exposed ridge crests and mountain summits in areas of strong geostrophic winds,
- F) exposed coastal sites in areas of strong geostrophic winds,
- G) exposed coastal sites in areas of strong surface pressure/thermal gradients.

For the purpose of this discussion, an average wind power density in excess of 200 watts/m² at 10 m will identify the high wind energy areas. Figure 5 shows the locations of these areas in the Northwest, designated by the letters above corresponding to the type of indicator(s). For example, areas labeled "A" in Figure 5 are corridors where frequent strong surface-pressure gradients occur during the season(s) of high wind energy. Very few places in the Northwest have high wind energy during every season. An area with an annual average of 200 to 250 watts/m² at 10 m (class 4) might have only one or two seasons of high wind energy. (For a description of the wind power maps, see pages 217 to 219).

Examples of type "A" include the Columbia River corridor of Washington and Oregon, the central Washington corridor near Ellensburg, the southwest Montana corridors near Livingston and Whitehall, and the southern Wyoming corridors. An interesting feature of the Columbia River and central Washington corridors is that the high wind energy zone extends 50 to 100 km east of the mountains into the basin. Other corridors of this type exist in the Northwest where moderate to high wind energy may occur during one season, but the annual average power is estimated at less than 200 watts/m². Such areas include the east end of the Strait of Juan de Fuca in Washington (summer high), the La Grande area in Oregon (winter high), and the southern Idaho corridors, such as the Strevell area (winter high).

Type "B" areas may coincide with type "A" but may also have high winds in the absence of strong surface pressure gradients. For example, in southwest Montana, strong westerly winds aloft are channeled down the long valleys aligned southwest to northeast and extending down from the mountain ranges. Highest wind speeds typically occur near the mouth of the valley. These include the areas of Livingston, Whitehall, and Harlowton, Montana, and Cody, Wyoming. The season of highest wind power in type "B" areas is usually winter, the season of strongest winds aloft.

A wide gap, 100 to 200 km wide, in the Rocky Mountain chain exists in southern Wyoming. This area can be considered a relatively high elevation plain, at an elevation of 2000 to 2500 m, containing isolated hills and ridges. Strong winds are usually associated with the occurrence of strong westerly and southwesterly geostrophic winds, which are strongest during the winter. Although most of the existing wind data used in the analysis is a narrow band along the major highway system running east to west through southern Wyoming, high energy is expected to exist throughout the open high plains in southern Wyoming.

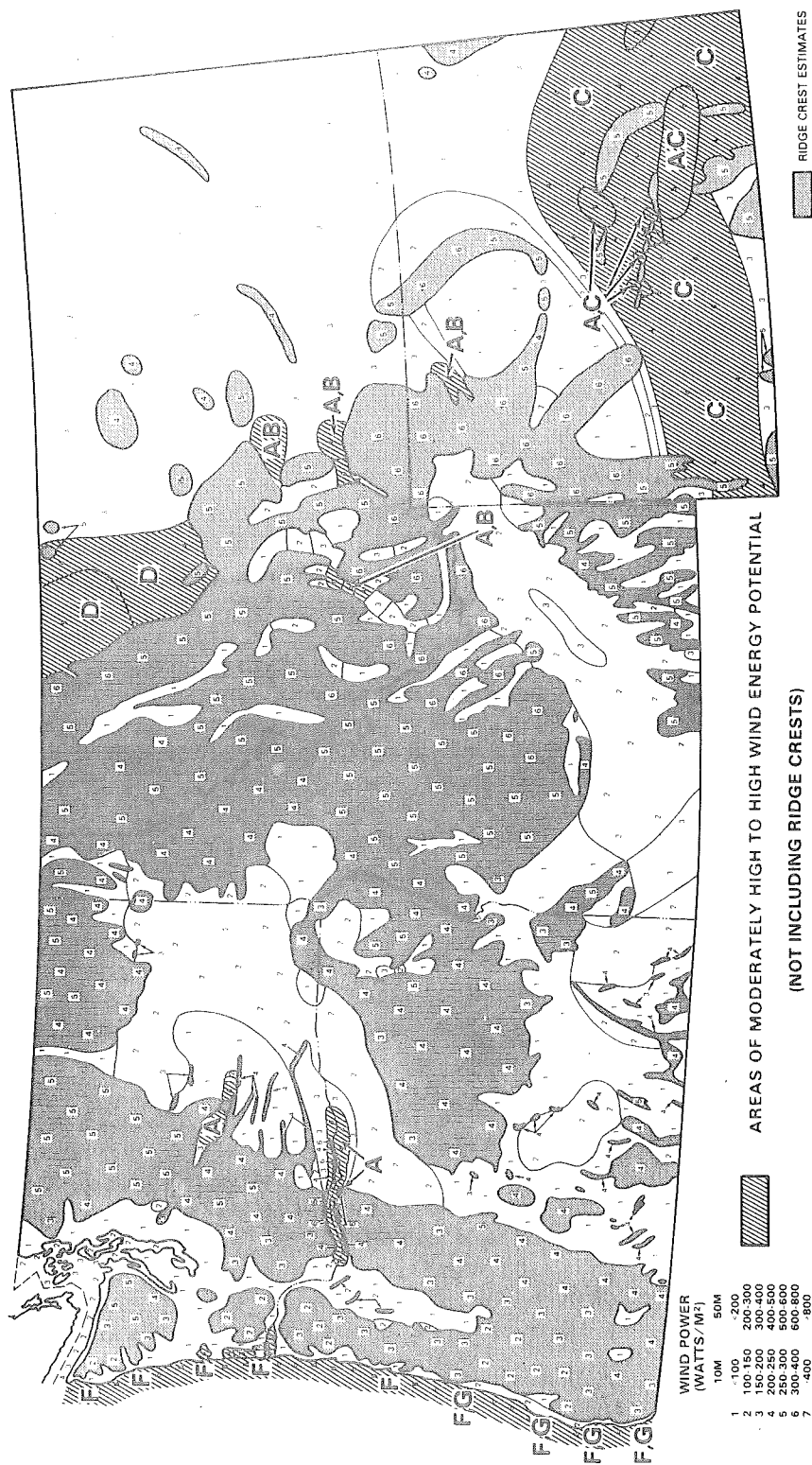


FIGURE 5. Northwest Annual Average Wind Power Map Highlighting the Areas of High Wind Energy Potential. Letters A through G designate the indicator types.

The northwest Montana plains, eastward from the abrupt edge of the Rocky Mountains to about Cut Bank, Montana, experience frequent strong southwest and west winds from late fall to spring, due to intense pressure gradients along the Rocky Mountains (type "D"). This flow is usually strongest in northwest Montana but extends southeastward to Billings, Montana. The highest wind energy is during the winter months.

Exposed coastal sites along the entire Northwest coast receive high wind energy during the winter, whereas only the central and southern Oregon coasts receive high wind energy during the summer. During the winter, the high winds are associated with frequent storms and the strong prevailing westerlies aloft. The wind energy is rapidly attenuated inland from the shore, because of increased roughness due to vegetation and topography. During the summer, strong northerly winds along the central and southern Oregon coast are associated with the strong surface pressure gradients created by the cold water and hot interior.

Although very limited wind data have been collected at mountain summits and ridge crests on an annual basis, rawinsonde observations indicate high annual wind energy potential at the heights of exposed ridge crests throughout the mountainous areas of the Northwest, except for the Coast Range in Oregon and Washington. Winter is the season with the strongest geostrophic winds throughout the Northwest, and thus the season of maximum wind power over exposed ridge crests. Although the mountainous regions occupy over a third of the Northwest's area, less than 2% of this area may be suitable for wind turbine siting.

Low wind power areas ($<100 \text{ watts/m}^2$ at 10 m), as shown in Figure 6, are associated with:

- H) valleys perpendicular to the prevailing wind direction aloft,
- I) sheltered basins,
- J) short and/or narrow valleys and canyons,
- K) areas of high surface roughness.

Basins and valleys are typically poor wind resource areas because of the sheltering effects of surrounding terrain. Moreover, cold stable air frequently fills these lower areas during the colder months, further inhibiting the transfer of momentum from aloft. Thus, the wind energy in sheltered basins and valleys are generally light year-round. Although only very limited wind data were available in some of the areas depicted in Figure 6, such as the basins of southern Oregon, eastern Idaho, and northwest Wyoming, these areas have characteristic features that are indicative of low wind energy.

Over areas of high roughness, such as forested and urban areas, the wind power in the lower 50 m is significantly reduced. As mentioned earlier, this is readily apparent in the rapid attenuation of wind power inland from the Pacific Ocean. In western Washington even exposed airport sites, such as the Seattle-Tacoma International Airport, indicate low wind power.

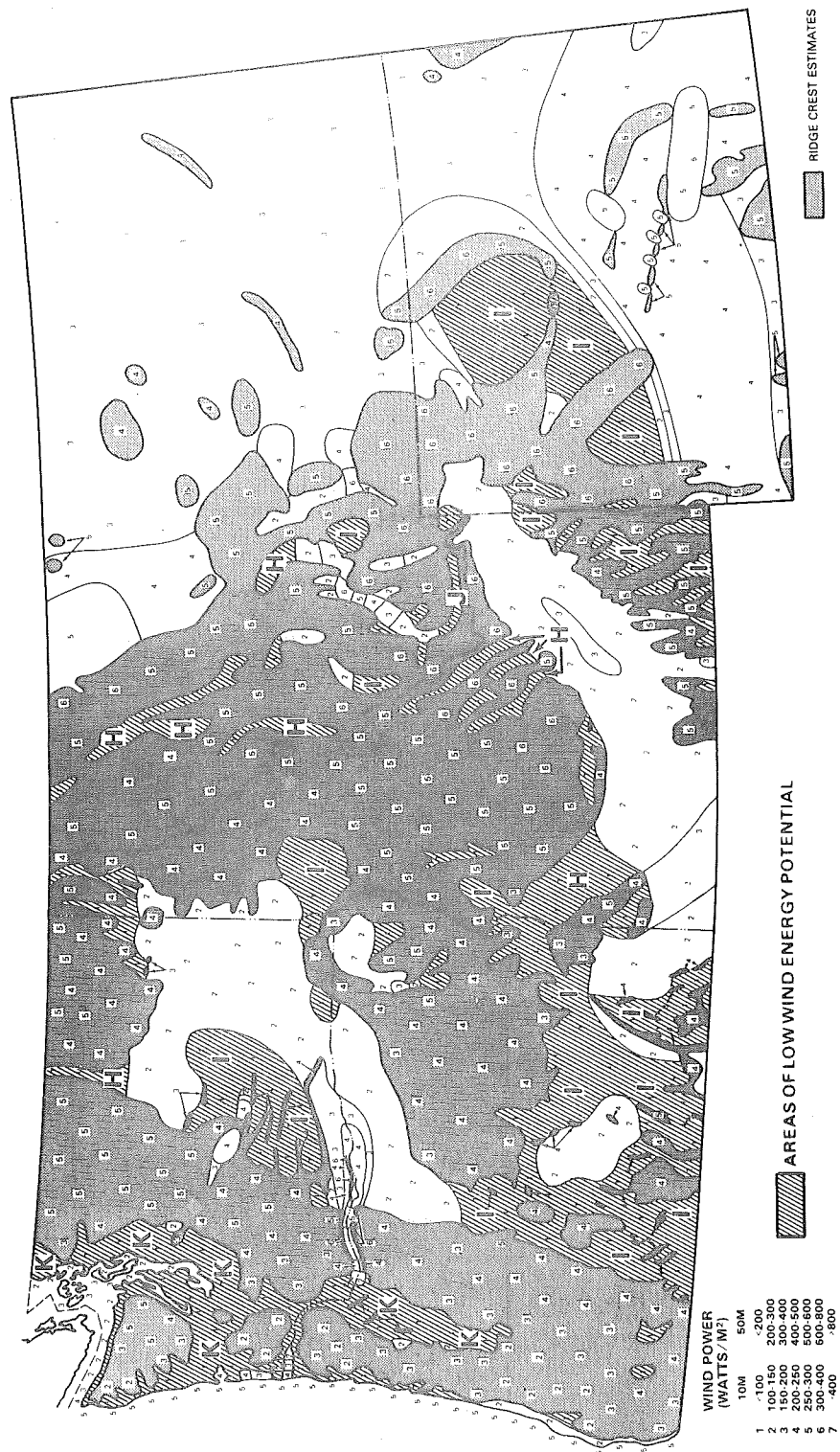


FIGURE 6. Northwest Annual Average Wind Power Map Highlighting the Areas of Low Wind Energy Potential. Letters H through K designate the indicator types.

CONCLUSIONS

Techniques using meteorological and topographical indicators of wind energy, developed by PNL and applied to the Northwest wind resource assessment, improved the reliability of the analysis of the geographical distribution of wind energy. The identification and application of these indicators led to an improved understanding of the conditions associated with high and low wind energy. Furthermore, these indicators are especially useful in complex terrain and wind-data-sparse areas for obtaining a somewhat realistic estimate of the wind energy resource.

REFERENCES

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